NOAA Technical Memorandum NESDIS NGDC-61

DIGITAL ELEVATION MODEL OF HANALEI, HAWAII : PROCEDURES, DATA SOURCES AND ANALYSIS

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1. Introduction

In March 2011 The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated bathymetric–topographic digital elevation model (DEM) of Hanalei, Hawaii (Fig. 1). A 1/3 arc-second[1] DEM of Hanalei, Hawaii referenced to mean high water (MHW) was carefully developed and evaluated. The DEM will be used as input for the Method of Splitting Tsunami (MOST) model developed by Pacific Marine Environmental Laboratory (PMEL) NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/) to simulate tsunami generation, propagation and inundation. The MHW DEM was generated from diverse digital datasets in the region (grid boundary and sources shown in Fig. 3) for tsunami inundation modeling, as part of the tsunami forecast system Short-term Inundation Forecasting for Tsunamis (SIFT) currently being developed by PMEL for the NOAA Tsunami Warning Centers. This report provides a summary of the data sources and methodology used in developing the DEM.

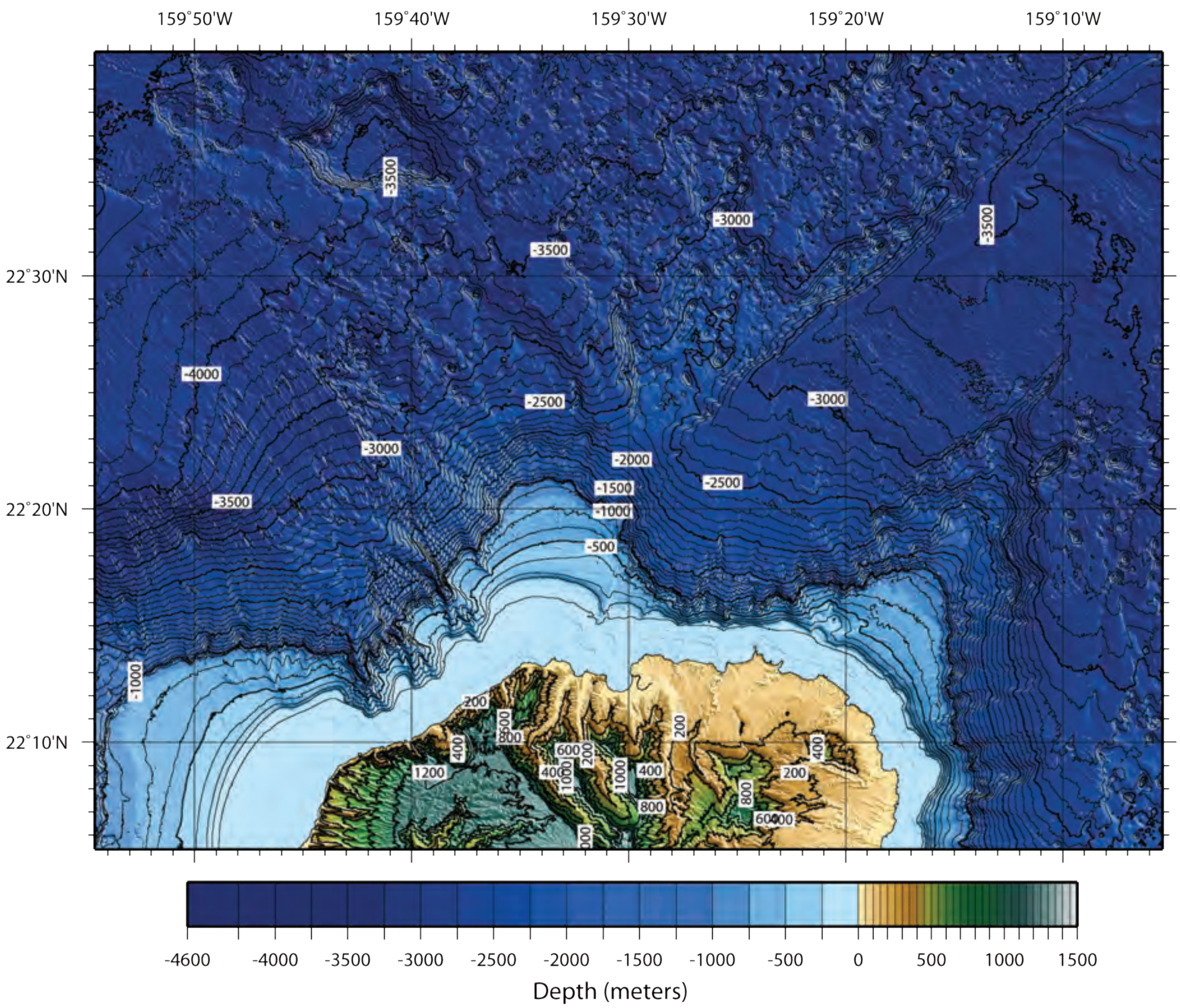

Figure 1. Shaded relief image of the Hanalei, Hawaii DEM. Contour intervals for bathymetry are 100 meters and 200 meters for topography.

1. The Hanalei, Hawaii DEM was built upon a grid of cells that are square in geographic coordinates (latitude and longitude), however, the cells are not square when converted to projected coordinate systems such as UTM zones (in meters). At the latitude of Hanalei, Hawaii, (22° 12′ 24″ N, 159° 30′ 3″ W) 1/3 arc-second of latitude is equivalent to 10.25 meters; 1/3 arc-second of longitude equals 9.55 meters.

2. Study Area

The Hanalei DEM covers the northern coast of the island of Kauai, the northern most island of the main Hawaiian Island Chain (Fig. 2). Hawaii is at risk from tsunamis caused by both distant and local sources. While most tsunamis that affect Hawaii originate from distant areas where tectonic plates collide (subduction zones), such as Alaska's Aleutian Island chain, Japan, and the west coast of South America, regional shallow undersea earthquakes or landslides can generate local tsunamis. What poses the most danger for residents is the shorter warning time for locally generated tsunamis, from hours to minutes notice.

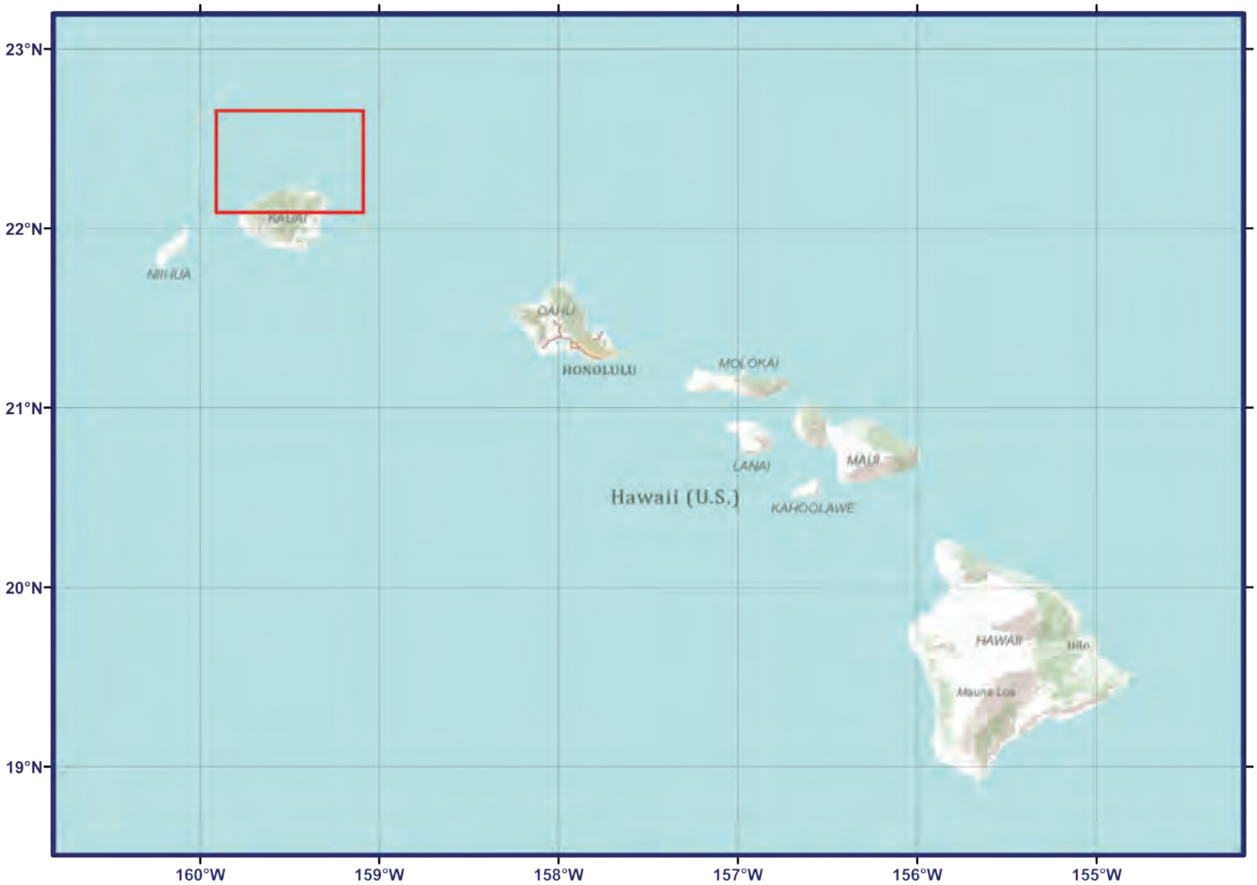

Figure 2. Map of the Hawaiian Island Chain and the location of the Hanalei, Hawaii DEM boundary, shown as red box.

3. Methodology

The Hanalei MHW DEM was constructed to meet PMEL specifications (Table 1), based on input requirements for the development of reference inundation models (RIMs) and standby inundation models (SIMs) (*V. Titov, pers. comm.*) in support of NOAA's Tsunami Warning Center use of SIFT to provide real-time tsunami forecasts in an operational environment. The best available bathymetric and topographic digital data were obtained by NGDC and shifted to common horizontal and vertical datums: North American Datum of 1983[2] (NAD 83) and MHW, for modeling of maximum flooding. Data were gathered in an area slightly larger (~5%) than the DEM extents. This data "buffer" ensures that gridding occurs across rather than along the DEM boundaries to prevent edge effects. Data processing and evaluation, and DEM assembly and assessment are described in the following subsections.

Table 1. PMEL specifications for the 1/3 arc-second Hanalei, Hawaii DEM.

Grid Area	Hanalei, Hawaii
Coverage Area	159.09º to 159.91º W; 22.09º to 22.66º N
Coordinate System	Geographic decimal degrees
Horizontal Datum	World Geodetic System of 1984 (WGS 84)
Vertical Datum	Mean high water (MHW)
Vertical Units	Meters
Cell Size	1/3 arc-second
Grid Format	ESRI ASCII raster grid

2. The horizontal difference between the North American Datum of 1983 (NAD 83) and World Geodetic System of 1984 (WGS 84) geographic horizontal datums is approximately one meter across the contiguous U.S., which is significantly less than the cell size of the DEMs. Most GIS applications treat the two datums as identical, so do not actually transform data between them, and the error introduced by not converting between the datums is insignificant. NAD 83 is restricted to North America, while WGS 84 is a global datum. As tsunamis may originate most anywhere around the world, tsunami modelers require a global datum, such as WGS 84 geographic, for their DEMs so that they can model the wave's passage across ocean basins. These DEMs are identified as having a WGS 84 geographic horizontal datum even though the underlying elevation data were typically transformed to NAD 83 geographic. At the scale of the DEMs, WGS 84 and NAD 83 geographic are identical and may be used interchangeably.

3.1 Data Sources and Processing

Shoreline, bathymetric, and topographic digital datasets (Fig. 3) were obtained from several U.S. federal, state and local agencies, and academic institutions including: NGDC; NOAA's National Ocean Service (NOS), Office of Coast Survey (OCS), Center for Coastal Monitoring and Assessment (CCMA); Coastal Services Center (CSC), and Pacific Services Center (PSC); the County of Kauai Information Technology Division; the Federal Emergency Management Agency (FEMA); the U.S. Army Engineer Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX); and the U.S. Geological Survey (USGS). Safe Software's *FME* data translation tool package was used to shift datasets to NAD 83 geographic horizontal datum and to convert them into ESRI *ArcGIS* shapefiles[3]. The shapefiles were then displayed with *ArcGIS* and Applied Imagery's *Quick Terrain Modeler* (*QT Modeler*) to assess data quality and manually edit datasets. Vertical datum transformations to MHW were accomplished using NOAA's tide station information. ESRI's online *World 2D* imagery was used to analyze and modify data. *QT Modeler*, *Gnuplot* and Interactive Visualization System's *Fledermaus* software were used to evaluate processing and gridding techniques.

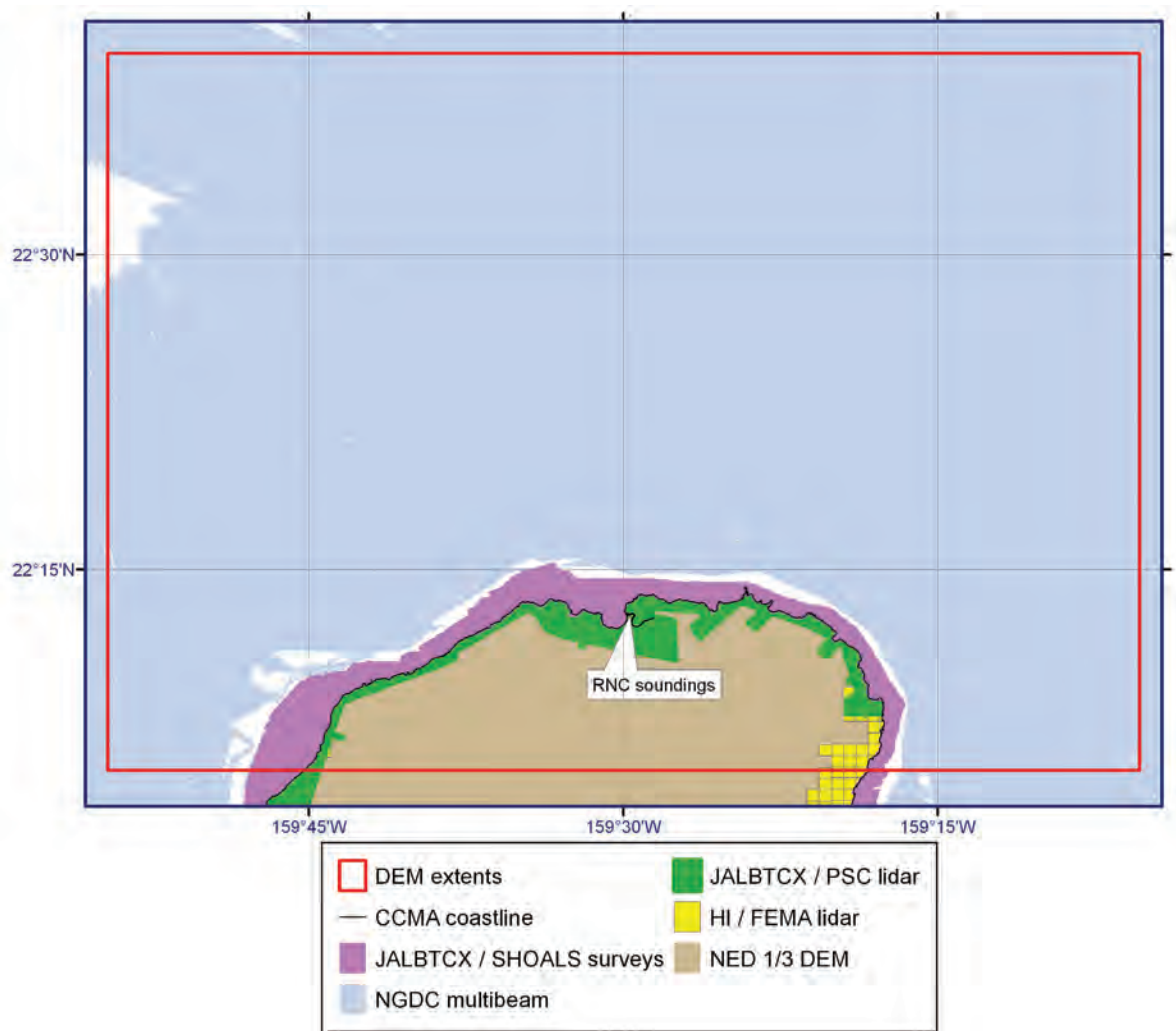

Figure 3. Source and coverage of datasets used in building the Hanalei, Hawaii DEM.

3. *FME* uses the North American Datum Conversion Utility (NADCON; http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.shtml) developed by NOAA's National Geodetic Survey (NGS) to convert data from NAD 27 to NAD 83. NADCON is the U.S. Federal Standard for NAD 27 to NAD 83 datum transformations.

3.1.1 Coastline

Coastline datasets of the Hanalei, Hawaii region were obtained from NOAA's OCS as Electronic Navigational Charts (ENCs)[4], and Center for Coastal Monitoring and Assessment (CCMA) Biogeography division. Comparisons between the two showed the CCMA coastline more consistent with ESRI's *World 2D* imagery, *Google Earth* and IKONOS imagery (Table 2; Fig. 4).

Table 2. Shoreline dataset used in building the Hanalei, Hawaii DEM.

Source	***Year***	***Data Type***	***Spatial Resolution***	***Original Horizontal Datum/Coordinate System***	***Original Vertical Datum***	***URL***
CCMA	2004 to 2006	Vector shoreline	1:6,000	NAD 83 UTM Zone 4 North (meters)	Unknown	http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd_07/welcome.html

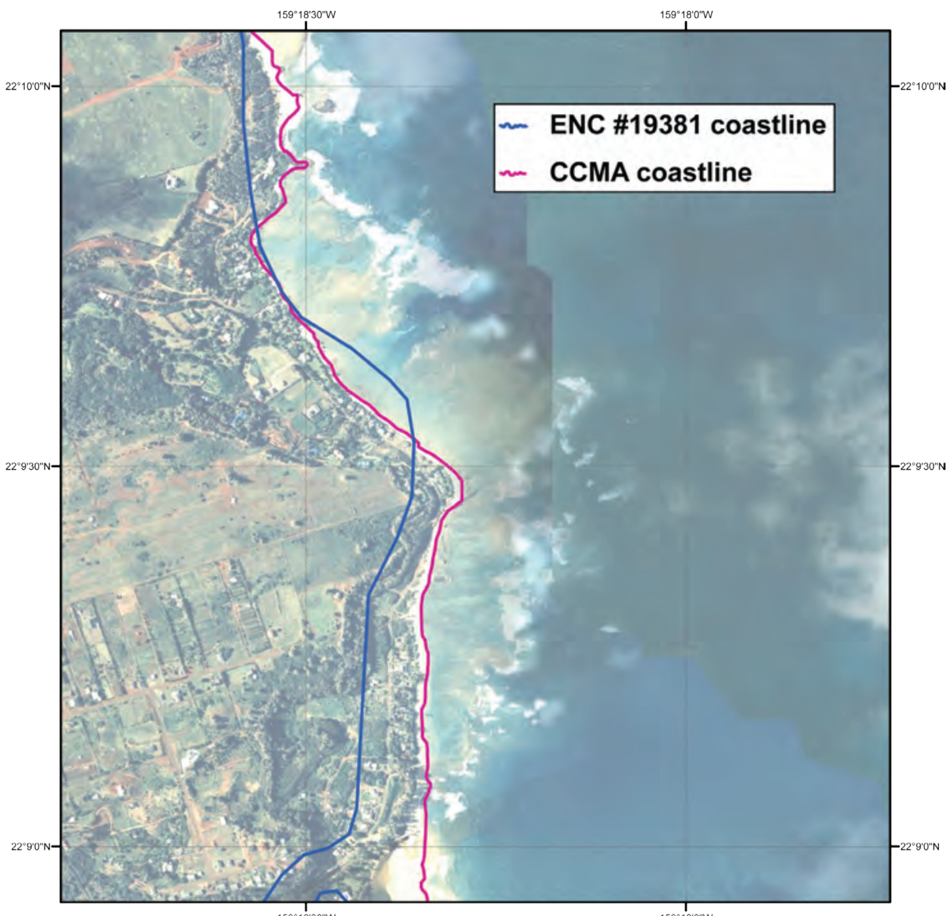

Figure 4. Comparison of ENC MHW shoreline and CCMA coastline

4. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://nauticalcharts.noaa.gov/mcd/enc/]

The CCMA Kauai shoreline dataset was downloaded from the CCMA Biodiversity web page in shapefile format and transformed to NAD 83 geographic using *ArcCatalog*. The data was derived from IKONOS and Quickbird Satellite Imagery from 2004 to 2006. In mapping the coral reef habitats of the Main Eight Hawaiian Islands by visual interpretation and manual delineation of IKONOS and Quick Bird satellite imagery, this shapefile was created from the shoreline digitized during this process.

The CCMA coastline was clipped to 0.05 degrees larger than the Hanalei, Hawaii DEM boundary. Piers and docks within Hanalei, Hawaii were deleted from the coastline. The coastline was further modified based on *Google Earth* imagery to reflect the most current coastal morphology. An xyz file of the “combined coastline” with points every 10 meters was generated using NGDC’s *GEODAS* software for use in creating a bathymetric surface (see Section 3.3.2).

3.1.2 *Bathymetry*

Bathymetric datasets used in the compilation of the Hanalei, Hawaii DEM included: NGDC multibeam swath sonar surveys, U.S. Army Engineer Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) SHOALS lidar, and NOAA RNC chart soundings (Table 3; Fig. 3). NOS hydrographic surveys were reviewed but not used as newer data overlapped the surveys or due to the age of the survey. Datasets were originally horizontally referenced to WGS 84 geographic. The data are vertically referenced to mean lower low water (MLLW) or mean sea level (MSL).

Table 3. Bathymetric datasets used in compiling the Hanalei, Hawaii DEM.

Source	***Year***	***Data Type***	***Spatial Resolution***	***Original Horizontal Datum/Coordinate System***	***Original Vertical Datum***	***URL***
JALBTCX SHOALS	1999	Hydrographic lidar survey	~ 5 to 10 meters	WGS 84 geographic	MLLW	http://shoals.sam.usace.army.mil/hawaii/pages/Hawaii_Data.htm
NGDC	1995 to 2010	Multibeam swath sonar surveys	Raw sonar files gridded to 1 arc-second	WGS 84 geographic	Assumed MSL (meters)	http://www.ngdc.noaa.gov/mgg/bathymetry/multibeam.html
NOAA RNC	2008	Digitized NOAA nautical chart soundings	10 meters	WGS 84 geographic	MLLW (meters)	http://nauticalcharts.noaa.gov/mcd/enc/

1) U.S. Army Engineer Joint Airborne Lidar Bathymetry Technical Center of Expertise (JALBTCX) hydrographic lidar surveys

JALBTCX conducted high-resolution hydrographic lidar surveys around Kauai in 1999 and 2000 (Table 4; Fig. 5). These surveys were originally referenced to WGS 84 geographic and MLLW vertical datum (meters). The resolution of the surveys range from roughly 5 to 10 meters and the depths range from -1.1 to -11.3 meters at MHW.

Table 4. JALBTCX / SHOALS hydrographic surveys used in compiling the Hanalei, Hawaii DEM.

Survey name	*Date*	*Resolution*	*Original Horizontal Datum*	*Original Vertical Datum*
Kauai 3	1999	~ 5 to 10 meters	WGS 84 geographic	MLLW
Kauai 4	1999	~ 5 to 10 meters	WGS 84 geographic	MLLW
Kauai 5	1999	~ 5 to 10 meters	WGS 84 geographic	MLLW
Kauai 6	1999	~ 5 to 10 meters	WGS 84 geographic	MLLW

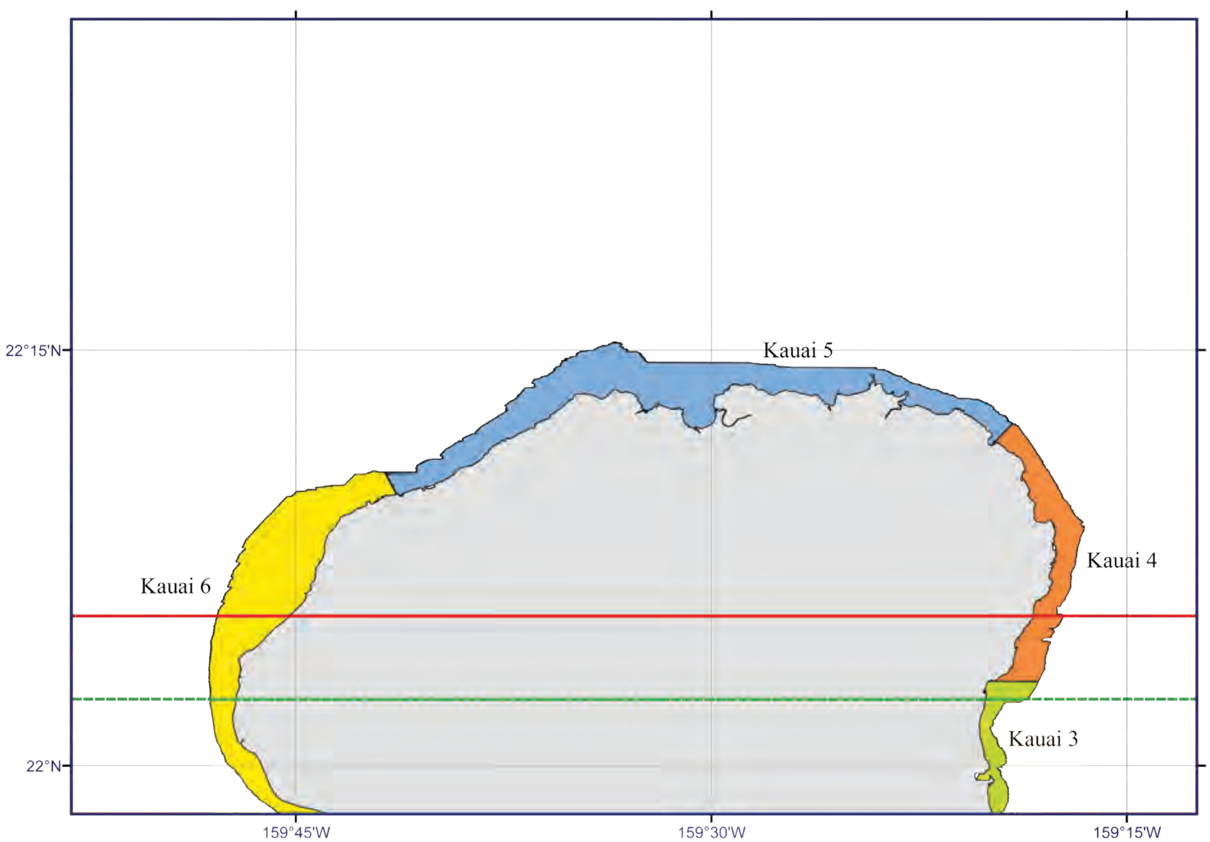

Figure 5. Spatial coverage of the JALBTCX / SHOALS hydrographic lidar surveys used in developing the Hanalei DEM. Red solid line denotes the DEM boundary and the green dashed line denotes extent of data (See Sec. 3.0).

2) NOAA NGDC multibeam database surveys

Twenty-four multibeam swath sonar surveys (Table 5, Fig. 6) are available from the NGDC multibeam sonar bathymetry database for the Hanalei DEM region. This database is comprised of the original swath sonar files of surveys conducted mostly by the U.S. academic fleet. Two of these surveys were not used in building the DEM due to poor quality of returns throughout the survey. Surveys are referenced to a horizontal datum of WGS 84 geographic and an undefined vertical datum, assumed to be essentially MSL.

The downloaded data were gridded to 1 arc-second resolution using *MB-System*[5]. Further editing of the gridded data was done using *QT Modeler* and clipped to JALBTCX SHOALS bathymetric lidar surveys. Two surveys, KRUS05RR and KM0326 required individual swath editing which was done using *MB-system* swath editing tools (Fig. 7).

Table 5. Multibeam swath sonar surveys used in compiling the Hanalei, Hawaii DEM.

Cruise ID	*Collecting Institution*	*Year*	*Ship*
AHI-06-09	National Oceanic and Atmospheric Administration (NOAA/NMFS)	2006	Ahi
AVON06MV	University of California, Scripps Institution of Oceanography (UC/SIO)	1999	Melville
AVON07MV	UC/SIO	1999	Melville
AVOM08MV	UC/SIO	1999	Melville
CNTL12RR	UC/SIO	2003	Roger Revelle
COOK23MV	UC/SIO	2002	Melville
DRFT15RR	UC/SIO	2002	Roger Revelle
EW9508	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO)	1995	Maurice Ewing
HI-05-05	NOAA/NMFS	2005	Hi'ialakai
HI-06-09	NOAA/NMFS	2006	Hi'ialakai
HLY10TC	Columbia University, Lamont-Doherty Earth Observatory (CU/LDEO) / Rolling Deck to Repository (R2R) Program	2010	Healy
KIWI03RR	UC/SIO	1997	Roger Revelle
KM0326	University of Hawaii (UH) / Rolling Deck to Repository (R2R) Program	2003	Kilo Moana
KM0622	UH/R2R	2006	Kilo Moana
KM0710	UH/R2R	2007	Kilo Moana
KM0810	UH/R2R	2008	Kilo Moana
KRUS01RR	UC/SIO	2004	Roger Revelle
KRUS05RR	UC/SIO	2004	Roger Revelle
LFEX01MV	UC/SIO	2004	Melville
NBP0304	CU/LDEO	2003	Nathaniel B. Palmer
NBP0304B	CU/LDEO	2003	Nathaniel B. Palmer
VANC33MV	UC/SIO	2004	Melville

5. MB-System is an open source software package for the processing and display of bathymetry and backscatter imagery data derived from multibeam, interferometry, and sidescan sonars. The source code for MB-System is freely available (for free) by anonymous ftp (including "point and click" access through these web pages). A complete description is provided in web pages accessed through the web site. MB-System was originally developed at the Lamont-Doherty Earth Observatory of Columbia University (L-DEO) and is now a collaborative effort between the Monterey Bay Aquarium Research Institute (MBARI) and L-DEO. The National Science Foundation has provided the primary support for MB-System development since 1993. The Packard Foundation has provided significant support through MBARI since 1998. Additional support has derived from SeaBeam Instruments (1994-1997), NOAA (2002-2004), and others. [Extracted from MB-System web site; http://www.ldeo.columbia.edu/res/pi/MB-System/]

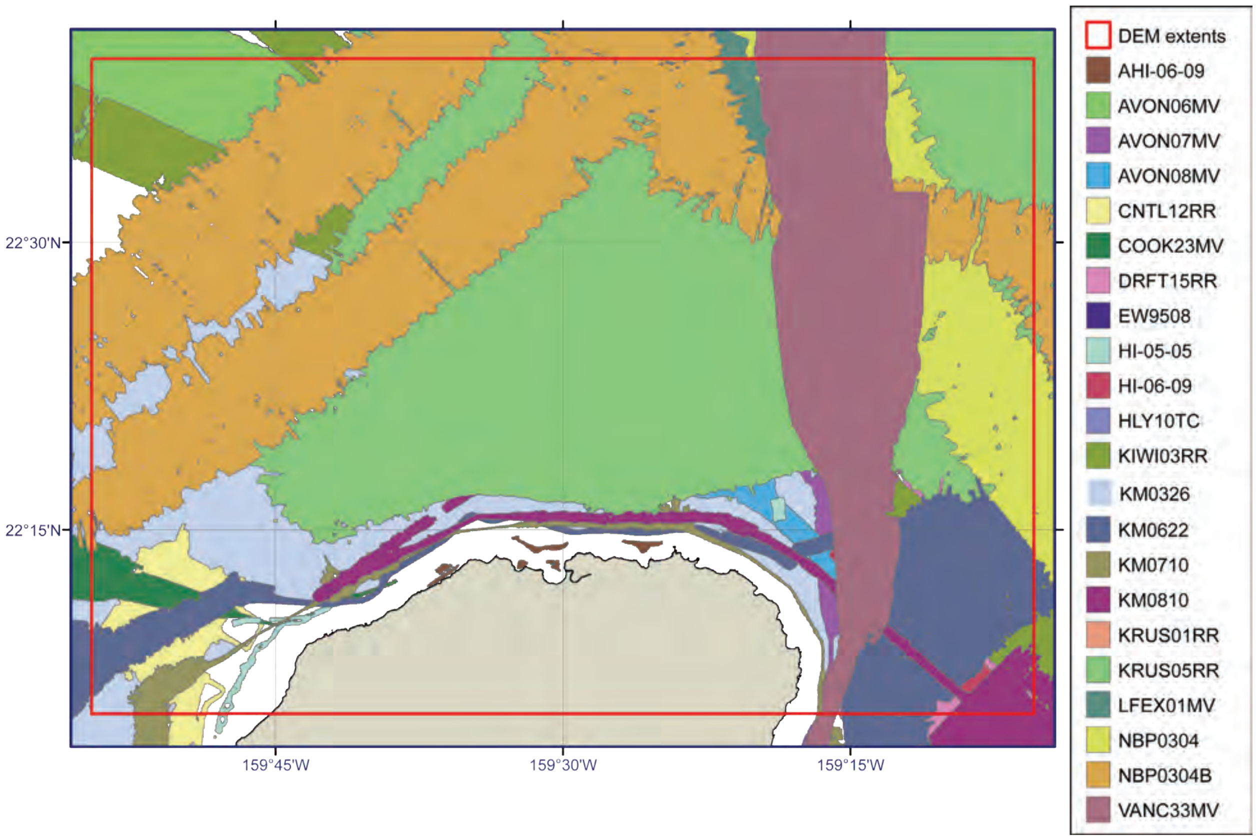

Figure 6. Spatial coverage of the NGDC multibeam survey data available in the Hanalei, Hawaii region.

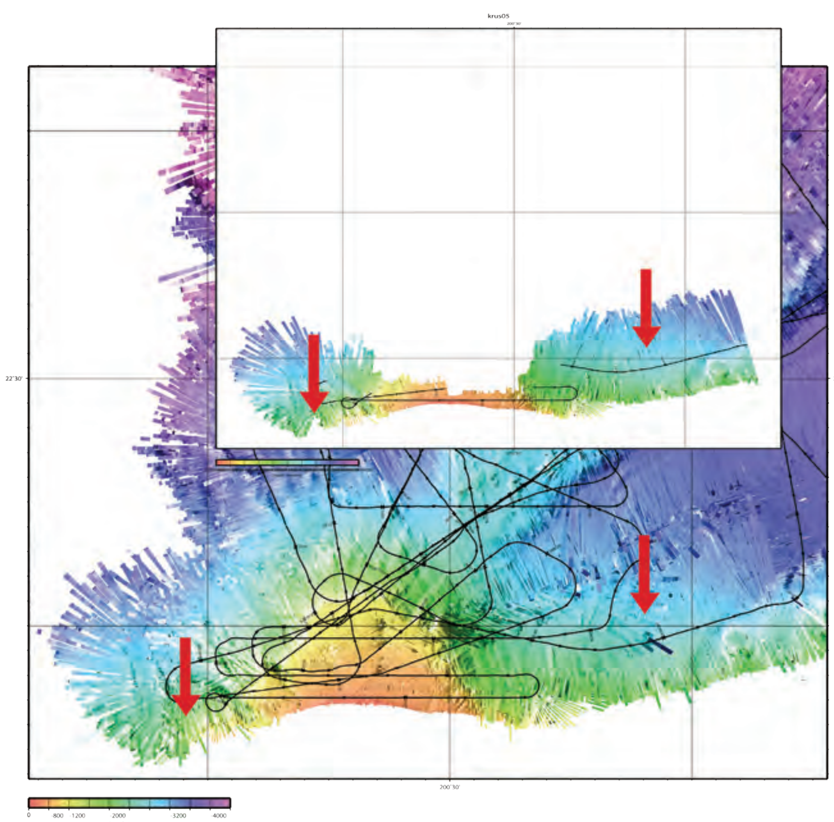

Figure 7. An example of swath edits made in multibeam survey KRUS05RR. Red arrows point to areas where returns were suspect and removed before re-gridding.

3) Digitized Nautical Chart soundings

Three NOAA Nautical charts are available from OCS in Raster Nautical Chart (RNC)[6] format within the Hanalei DEM boundary (Table 6). Sounding data from chart #19385 were digitized with depth values referenced to MLLW. The points were extrapolated to 10 meters apart using *GEODAS* and depth values were transformed to MHW using a constant value and converted to xyz format for use in creating a bathymetric pre-surface and in the final DEM. Figure 8 shows the coverage of the digitized soundings within the Hanalei Bay region.

Table 6. Nautical charts available in the Hanalei, Hawaii region.

Chart	*Title*	*Format*	*Edition*	*Issue Date*	*Scale*
19380	Oahu to Niihau	RNC	15	2003	1: 247,482
19381	Island of Kauai	ENC and RNC	3	2010	1:80,000
19385	North Coast of Kauai - Haena Point to Kepuhi Point	RNC	8	2003	1:20,000

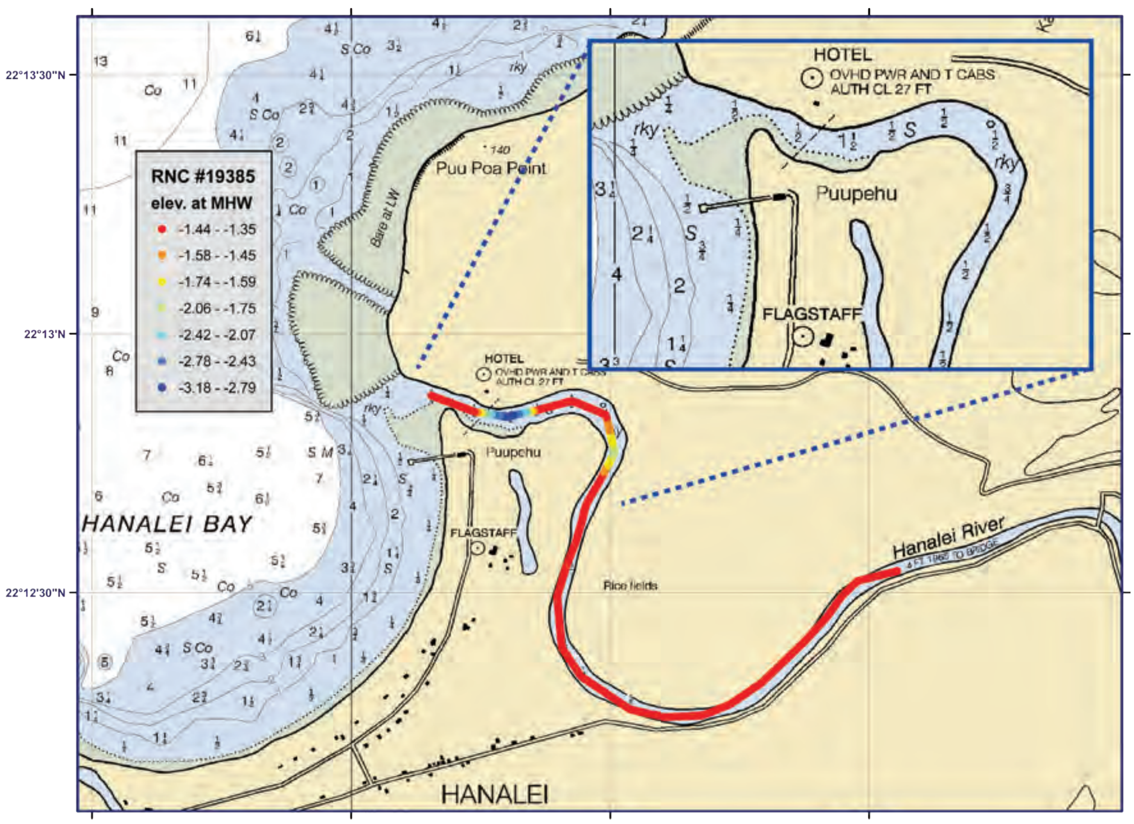

Figure 8. Spatial data coverage of digitized RNC soundings.

6. The Office of Coast Survey (OCS) produces NOAA Electronic Navigational Charts (NOAA ENC®s) to support the marine transportation infrastructure and coastal management. NOAA ENC®s are in the International Hydrographic Office (IHO) S-57 international exchange format, comply with the IHO ENC Product Specification and are provided with incremental updates, which supply Notice to Mariners corrections and other critical changes. NOAA ENC®s are available for free download on the OCS web site. [Extracted from NOAA OCS web site: http://nauticalcharts.noaa.gov/mcd/enc/]

3.1.3 *Topography*

Topographic datasets in the Hanalei, Hawaii region were obtained from: USGS, NOAA's Pacific Services Center (PSC), and the State of Hawaii Civil Defense (Table 7; Fig. 3). Ifsar data in DTM format for the entire island was available for use in building the Hanalei DEM but was not used due to the significant number of patches of interpolated data generated in areas of no data.

Table 7. Topographic datasets used in compiling the Hanalei, Hawaii DEM.

Source	*Year*	*Data Type*	*Spatial Resolution*	*Original Horizontal Datum/Coordinate System*	*Original Vertical Datum*	*URL*
USGS NED	2000	Topographic DEMs	1/3 arc-second grid	NAD 83 geographic	NAVD 88	http://seamless.usgs.gov/
State of Hawaii Civil Defense / FEMA	2006	Lidar	~ 3 feet	NAD 83 State Plane HI Zone 4 FIPS 5104 (feet)	Local tidal	
JALBTCX / PSC	2007	Lidar	1 meter data downloaded as 5 meter averaged grid	NAD 83 geographic	Mean Sea Level	

4) U.S. Geological Survey National Elevation Dataset topography

USGS National Elevation Dataset (NED) provides complete 1/3 arc-second coverage of the Hanalei, Hawaii region[7]. The dataset is available for download as raster DEMs in NAD 83 geographic horizontal datum and NAVD 88 (meters) vertical datum. The bare-earth elevations have a vertical accuracy of +/- 7 to 15 meters depending on source data resolution (see the USGS Seamless website for specific source information). The dataset was derived from USGS quadrangle maps and aerial photographs based on topographic surveys.

The USGS NED 1/3 arc-second DEM data were downloaded from the USGS website. *ArcCatalog* tools were used to clip the NED DEMs to the combined coastline. *FME* was used to convert the rasters to xyz format. Other higher resolution data were available to replace the NED data along the coast.

7. The USGS National Elevation Dataset (NED; http://ned.usgs.gov/) has been developed by merging the highest-resolution, best quality elevation data available across the United States into a seamless raster format. NED is the result of the maturation of the USGS effort to provide 1:24,000 scale Digital Elevation Model (DEM) data for the conterminous U.S. and 1:63,360 scale DEM data for California. The dataset provides seamless coverage of the United States, HI, CA, and the island territories. NED has a consistent projection (Geographic), resolution (1 arc-second), and elevation units (meters). The horizontal datum is NAD 83, except for Alaska, which is NAD 27. The vertical datum is NAVD 88, except for Alaska, which is NGVD 29. NED is a living dataset that is updated bimonthly to incorporate the "best available" DEM data. As more 1/3 arc-second (10 m) data covers the U.S., then this will also be a seamless dataset. [Extracted from USGS NED web site; http://ned.usgs.gov/]

5) **State of Hawaii Civil Defense / FEMA Lidar**

Pacific Services Center (PSC) provided NGDC with the State of Hawaii Civil Defense topographic lidar dataset. The lidar was flown in 2006 in support of hurricane study for the Hawaiian Islands and was specified to include coverage from the coastline up to the 10 meter contour elevation with an average point spacing of 3 feet. The data, in .las format 1.0 and ground last return (classification code 2) were projected to NAD 83 State Plane Hawaii Zone 4 FIPS 5104 (feet), and reference to local tidal datum, assumed to be local mean sea level. Data were converted to xyz format and transformed to NAD 83 geographic using *FME*.

6) **JALBTCX Hawaii lidar**

PSC provided lidar data from 2007 of the northern shoreline of Kauai. The purpose of the 2007 Hawaii survey, in general, was to collect both bathymetric and topographic lidar along the northern coastline of the Hawaiian Islands. Topographic data were required between the zero and 15 meter contours, nominal, for the northern coastline of the islands of Hawaii (Big Island), Kauai, Maui, Molokai, and Oahu. The data were to be collected from the land water interface seaward to a depth of 40 meters or laser extinction, whichever comes first. These data were collected for Hawaii State Civil Defense for tsunami mapping purposes. The one meter lidar data were gridded to 5 meters using an average grid method and referenced to NAD 83 geographic and mean sea level.

Figure 9 shows an example of the two lidar datasets and the area surrounding Anahola Bay on the eastern side of Kauai. The elevation values are very similar. Both data sets required automated clipping to the CCMA coastline to remove returns from the water.

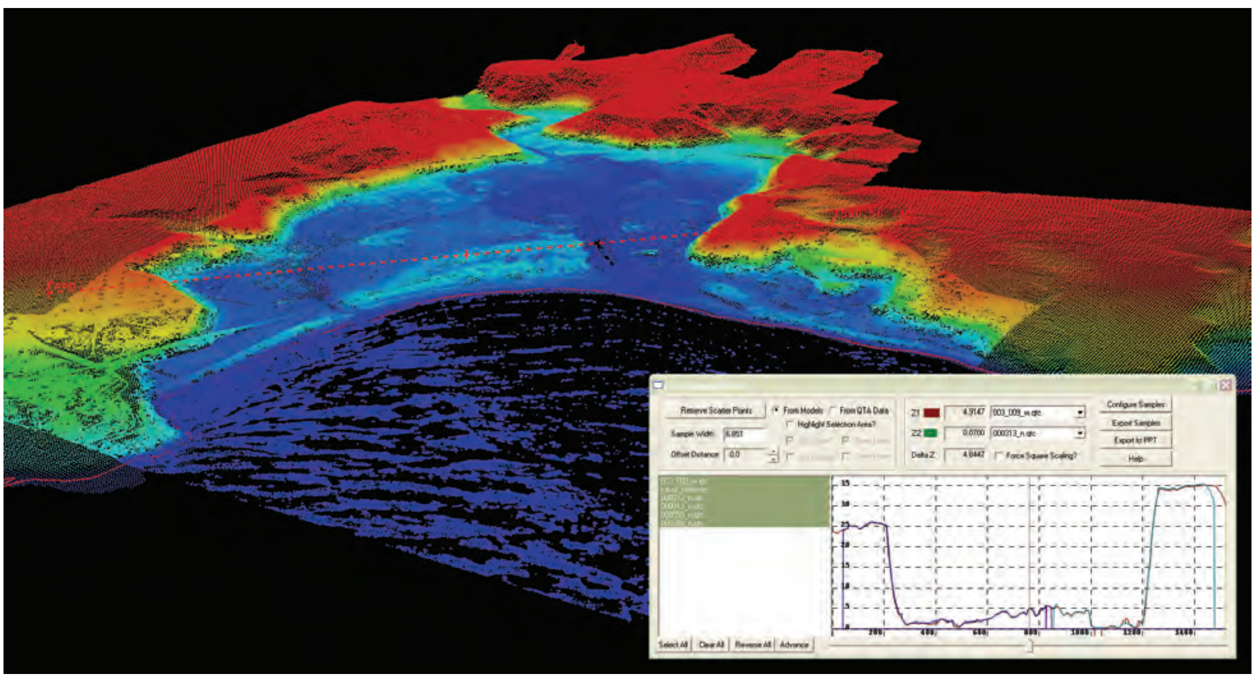

Figure 9. A comparison of FEMA and JALBTCX lidar at Anahola Bay. Cross section shows majority of elevation values match.

3.2 Establishing Common Datums

3.2.1 Vertical datum transformations

Datasets used in the compilation and evaluation of the Hanalei DEM were originally referenced to a number of vertical datums including: Local tidal datum, MLLW, MSL, and NAVD 88. All datasets were transformed to MHW using a constant value based on the average of the tide stations on Kauai. Locations of the tide stations are shown in Figure 16.

7) **Bathymetric data**

The multibeam surveys, the JALBTCX SHOALS data, and the nautical chart soundings were transformed from MSL, and MLLW to MHW, using a constant value. The average of the relationships between the various vertical datums and MHW based on two tide stations in the DEM region are listed in Table 8.

8) **Topographic data**

The NED DEM and the lidar data were originally referenced to NAVD 88, local tidal datum, or mean sea level. For this DEM, local tidal datum and mean sea level were assumed to be equal. As NAVD 88 does not exist on the Hawaiian Islands data referenced to NAVD 88 was also treated as mean sea level. Transformations from MSL to MHW were done using a constant value based on an average value of the two tide stations (Table 8).

Table 8. Relationships between MHW and other vertical datums in meters within the Hanalei, Hawaii DEM region.

	Nawiliwili Harbor	*Port Allen, Hanapepe Bay*	
MHHW	0.558	0.561	
MHW	0.434	0.439	
MTL	0.247	0.249	
MSL	0.252	0.254	
MLW	0.061	0.06	
NAVD 88	n/a	n/a	
MLLW	0	0	
	Difference in datums	*Difference in datums*	*Average of values*
MSL to MHW	-0.182	-0.185	-0.1835
MLLW to MHW	-0.434	-0.439	-0.4365

3.2.2 Horizontal datum transformations

Datasets used in compiling the Hanalei DEM were originally referenced to: NAD 83 and WGS 84 geographic; NAD 83 UTM Zone 4 North (meters); and NAD 83 State Plane Hawaii Zone 4 FIPS 5104 (feet) horizontal datums. The relationships and transformational equations between the geographic horizontal datums are well established and transformation to NAD 83 geographic were done using *FME* or *ArcGIS* software.

3.3 Digital Elevation Model Development

3.3.1 Verifying consistency between datasets

After horizontal and vertical transformations were applied, the resulting ESRI shapefiles were checked in ESRI *ArcMap* and *QT Modeler* for inter-dataset consistency. Problems and errors were identified and resolved before proceeding with subsequent gridding steps. The evaluated and edited ESRI shapefiles were then converted to xyz files in preparation for gridding. Problems included:

- Data values over the water in topographic datasets. Data required automated clipping to the combined coastline or manual editing.
- Inconsistent, overlapping bathymetric datasets. Lower-resolution datasets were clipped to higher-resolution data and all datasets were weighted based on quality and age in gridding process.

3.3.2 Smoothing of bathymetric data

In order to reduce the effect of artifacts in the form of lines of "pimples" in the 1/3 arc-second DEM due to variable resolution datasets, and to provide effective interpolation into the coastal zone, a 1 arc-second-spacing "pre-surface" or grid was generated using *GMT*[8].

The JALBTCX SHOALS surveys, RNC soundings, and NGDC multibeam swath sonar bathymetry data were combined into a single file. Points extracted every 10 meters from the combined coastline were also included and assigned elevation values of zero meters to ensure that the offshore elevations remained negative. These point data were then smoothed using the *GMT* tool "blockmedian" onto a 1 arc-second grid. The *GMT* tool "surface" was then applied to interpolate values for cells without data values. The *GMT* grid created by "surface" was converted into an ESRI Arc ASCII grid file using the *MB-System* tool "mbm_grd2arc". Conversion of this Arc ASCII grid file into an Arc raster permitted clipping of the grid with the combined coastline (to eliminate data interpolation into land areas).

The resulting surface was compared with original soundings to ensure grid accuracy, converted to an xyz file for use in the final gridding process (see Table 9). The statistical analysis of the differences between the 1 arc-second bathymetric surface and one multibeam survey showed that the majority of the soundings are in good agreement with the bathymetric surface (Fig. 10).

8. GMT is an open source collection of ~60 tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing Encapsulated PostScript File (EPS) illustrations ranging from simple x-y plots via contour maps to artificially illuminated surfaces and 3-D perspective views. GMT supports ~30 map projections and transformations and comes with support data such as GSHHS coastlines, rivers, and political boundaries. GMT is developed and maintained by Paul Wessel and Walter H. F. Smith with help from a global set of volunteers, and is supported by the National Science Foundation. It is released under the GNU General Public License. [Extracted from GMT web site; http://gmt.soest.hawaii.edu/]

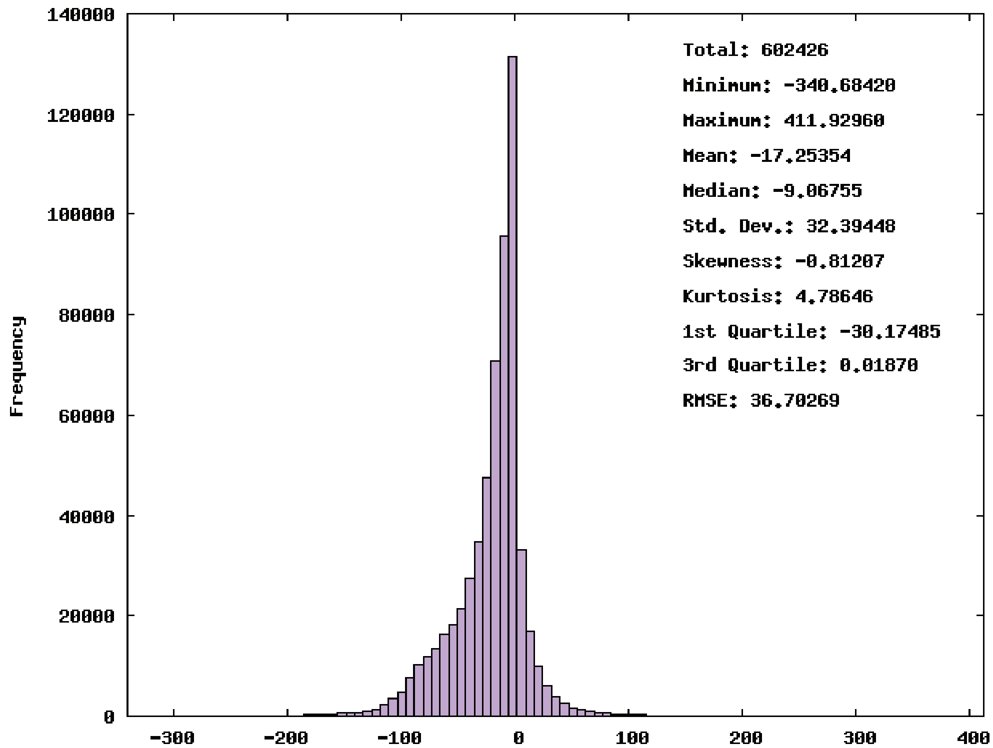

Figure 10. Histgram of differences between the 1 arc-second bathymetric surface and multibeam survey AVON07MV.

3.3.3 Building the 1/3 arc-second MHW DEM

MB-System was used to create 1/3 arc-second DEM of Hanalei, Hawaii. The *MB-System* tool "mbgrid" applied a tight spline tension to the xyz data, and interpolated values for cells without data. The data hierarchy used in the "mbgrid" gridding algorithm, as relative gridding weights, is listed in Table 9. Greatest weight was given to the RNC soundings and the bathymetric surface. Least weight was given to the deep water NGDC multibeam and NED DEM.

Table 9. Data hierarchy used to assign gridding weight in *MB-System*

Dataset	*Relative Gridding Weight*
RNC soundings	100
Bathymetric 'pre-surfaced' data	100
FEMA lidar	10
JALBTCX / PSC lidar	10
JALBTCX / SHOALS surveys	10
Combined coastline	10
USGS NED 1/3 DEM	1
NGDC multibeam data	1

3.4 Quality Assessment of the DEM

3.4.1 Horizontal accuracy

The horizontal accuracy of topographic and bathymetric features in the Hanalei, Hawaii DEM are dependent upon DEM cell size and the datasets used to determine corresponding DEM cell values. Topographic features inland have an estimated horizontal accuracy of less than 10 meters, based on the documented accuracy of the dataset. Lidar datasets have an accuracy of less than one meter. Gridded multibeam survey data have a positional accuracy of 10 meters. More recent JALBTCX / SHOALS bathymetric lidar data have accuracy of + / - 3 meters.

3.4.2 Vertical accuracy

Vertical accuracy of elevation values for the Hanalei DEM are also highly dependent upon the source datasets contributing to grid cell values. Topographic datasets have vertical accuracies of less than 1 meter, derived from FEMA and JALBTCX / PSC lidar data, and the NED topographic data has an estimated vertical accuracy of 10 meters. Bathymetric values, derived from single and multibeam sounding measurements, are 0.3 meters in 0 to 20 meters of water, 1.0 meters in 20 to 100 meters of water, and 1% of the water depth in 100 meters of water. Gridding interpolation to determine bathymetric values between sparse data degrades the vertical accuracy of elevations in deep water to about 5% of water depth. JALBTCX / SHOALS data have a vertical accuracy of 0.3 meter.

3.4.3 Slope map, 3-D perspective and data contribution plot

ESRI *ArcCatalog* was used to generate a slope grid from the 1/3 arc-second Hanalei DEM to allow for visual inspection and identification of artificial slopes along boundaries between datasets (Fig. 11). The DEM was transformed to NAD 83 UTM Zone 4 North coordinates (horizontal units in meters) in *ArcCatalog* for derivation of the slope grid; equivalent horizontal and vertical units are required for effective slope analysis. Dark areas indicate steeper slopes while lighter areas indicate low slope.

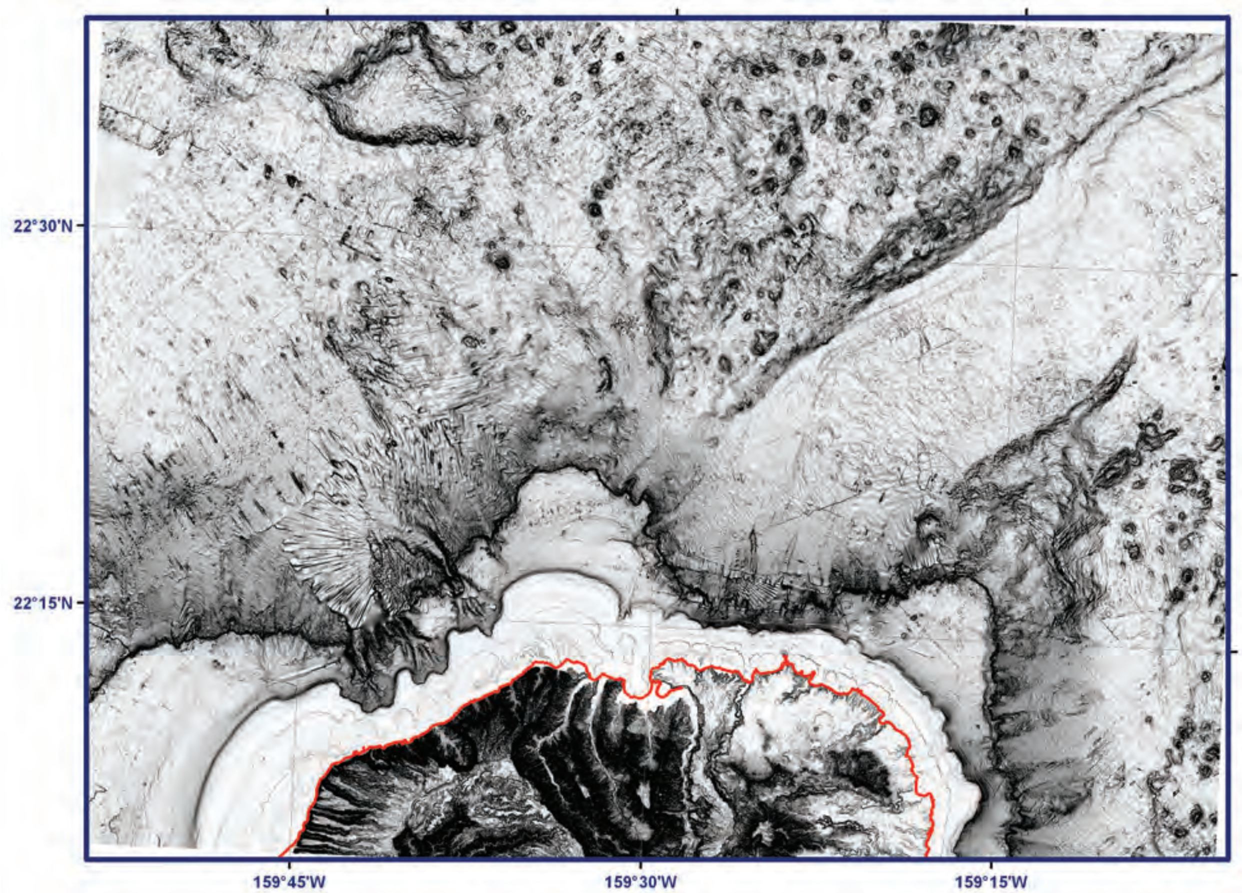

Figure 11. Slope map of the Hanalei DEM.

A high-resolution perspective image was generated using *Fledermaus,* providing three-dimensional viewing of the DEM (Fig. 12). Analysis of preliminary grids revealed suspect data points, which were corrected before recompiling the DEM.

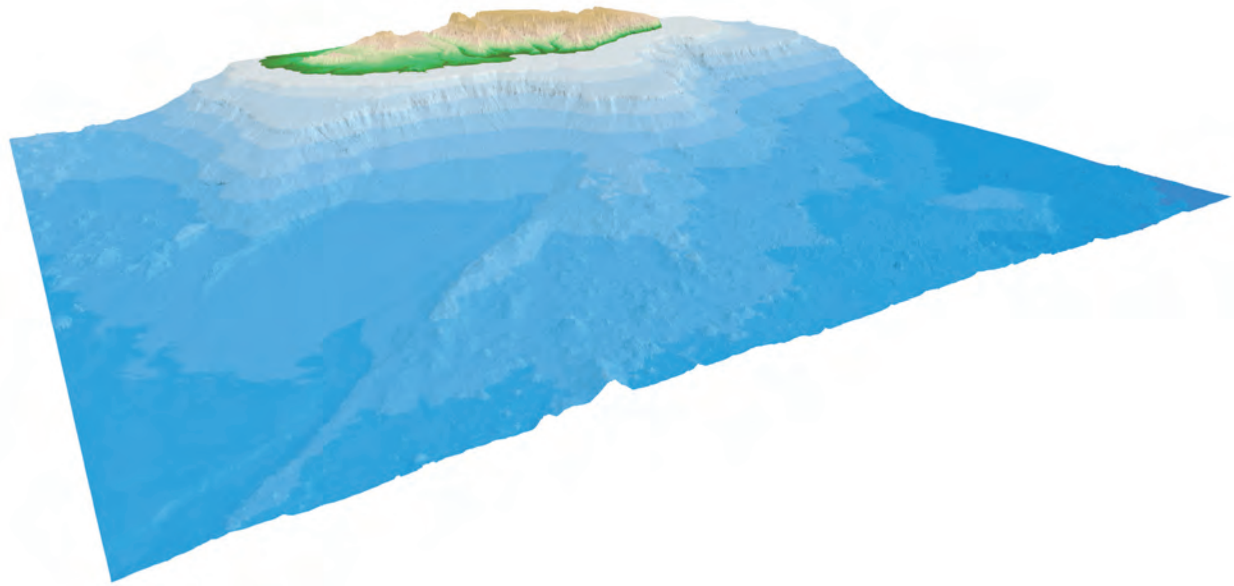

Figure 12. A perspective image of the Hanalei DEM. View is from the northeast and vertical exaggeration is 2x.

3.4.4 MHW DEM comparison with source data files

To ensure grid accuracy, the 1/3 arc-second Hanalei DEM was compared to select source data files. Large differences between the NBP0304B multibeam survey data and the Hanalei DEM occur where surveys overlap and in areas of rough terrain (Fig. 13).

A random sample of data files were used for comparing the high-resolution lidar topographic files to the DEM. Figures 14 and 15 show histograms of the differences between the DEM and two sample files of the lidar datasets. In both datasets, the largest differences between the lidar and the Hanalei DEM were located in areas of dense vegetation.

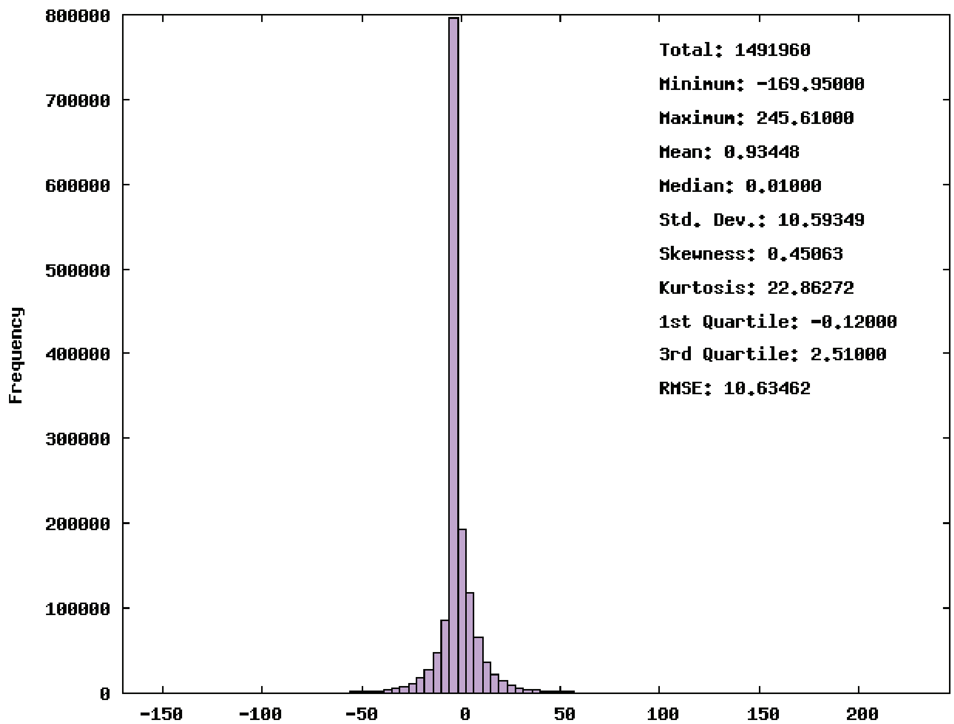

Figure 13. Histogram of the differences between the multibeam survey NBP0304B and the Hanalei DEM.

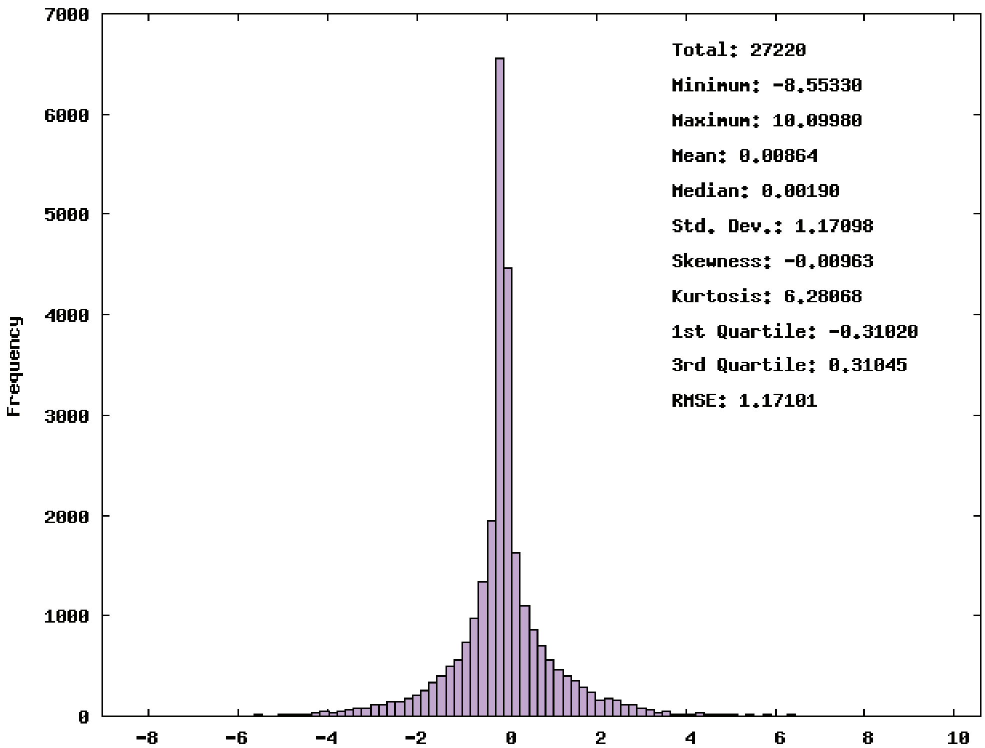

Figure 14. Histogram of differences between a sample set of JALBTCX / PSC lidar data and the Hanalei DEM.

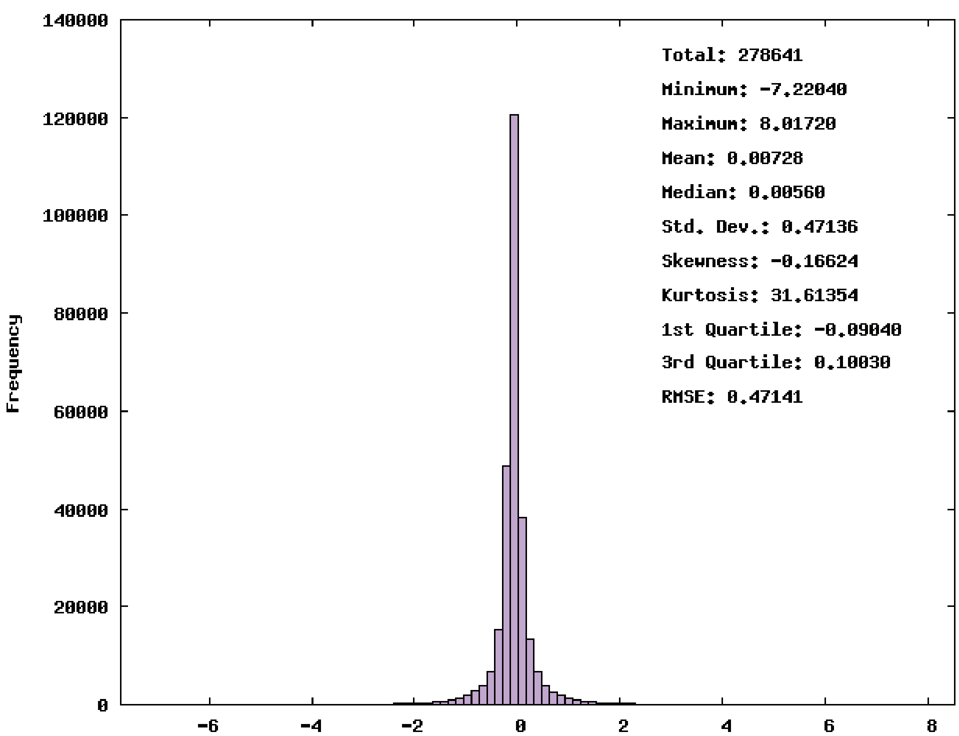

Figure 15. Histogram of differences between a sample set of FEMA lidar data and the Hanalei DEM.

3.4.5 Comparison with National Geodetic Survey geodetic monuments

The elevations of 118 geodetic monuments were extracted from the NOAA NGS web site (http://www.ngs.noaa.gov/) in shapefile format (see Fig. 16 for monument locations). Shapefile attributes give positions in NAD 83 geographic (typically sub-mm accuracy) and elevations in NAVD 88 (in meters). Elevations were compared to the Hanalei, Hawaii DEM. The largest difference, over 500 meters, is due to an error in either monument location or elevation. The monument elevation is recorded as 1151 meters in an area that is roughly 620 meters. Excluding this error, differences between the DEM and the monument elevations range from -6.05 to 40.78 meters, over 80% of which are within ± 5 meters (Fig. 17).

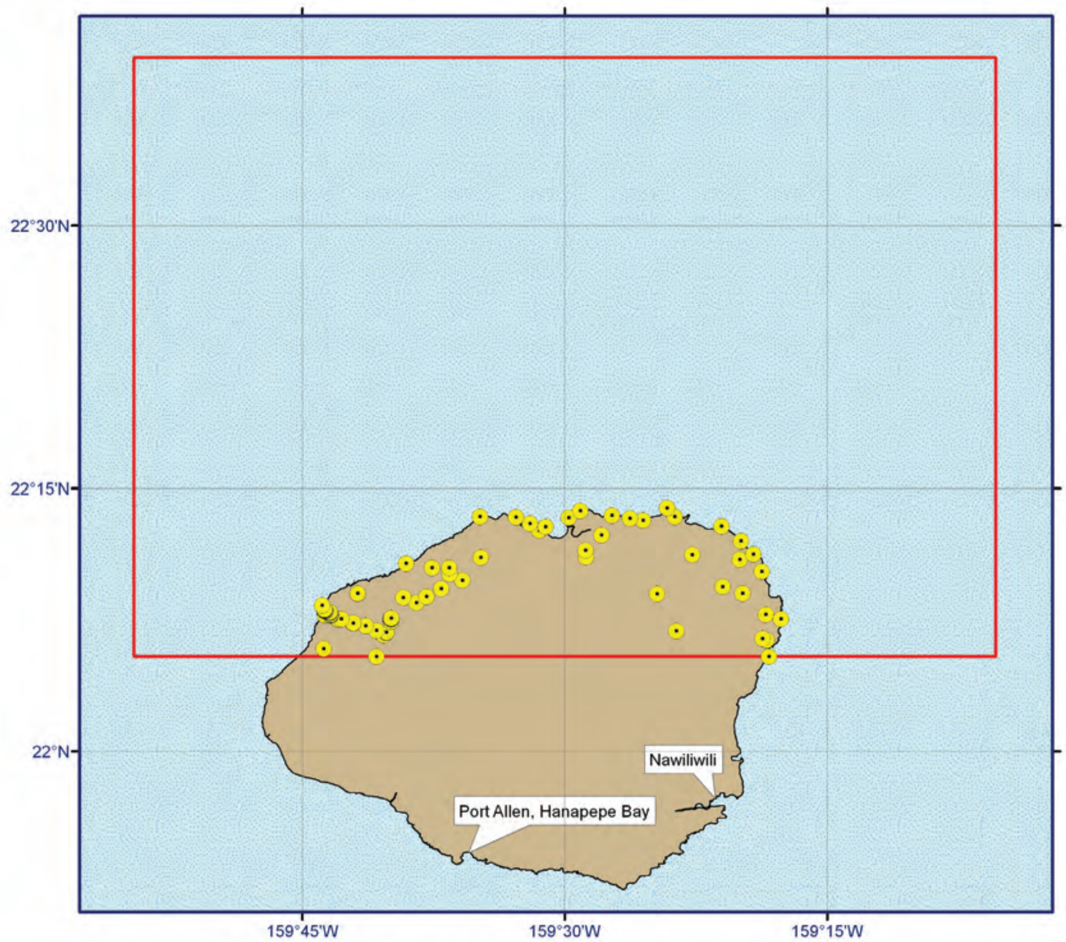

Figure 16. Location of NGS monuments within the Hanalei DEM boundary, in red. Tide stations are labeled.

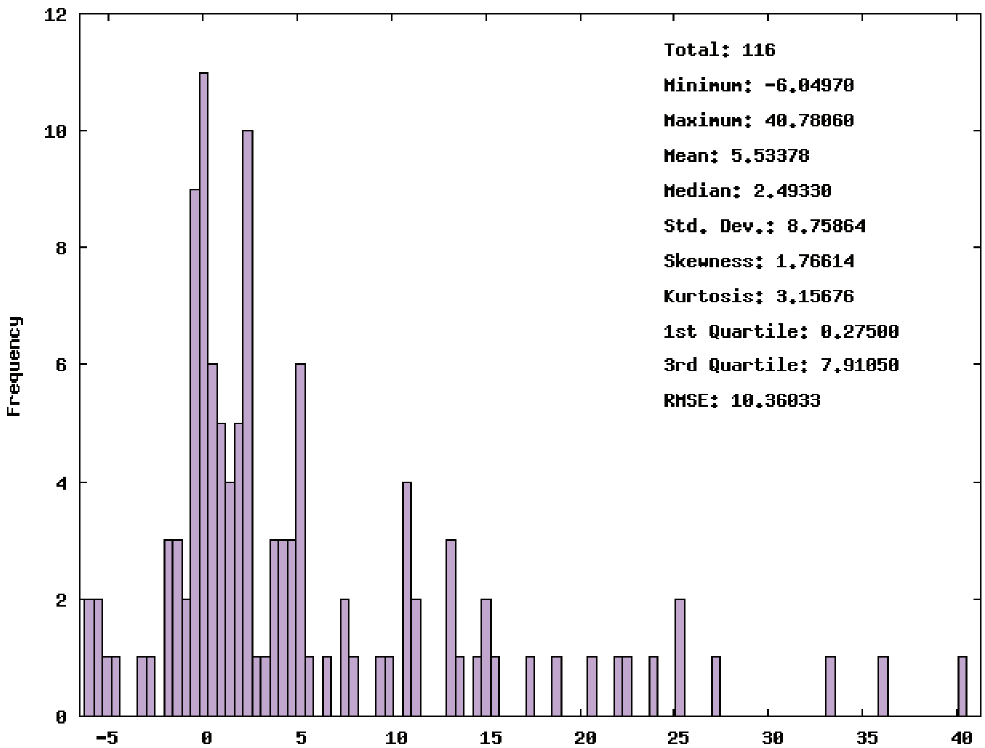

Figure 17. Histogram of the differences between the NGS monument elevations and the Hanalei DEM.

4. Summary and Conclusions

An integrated bathymetric–topographic DEM of Hanalei, Hawaii with cell size of 1/3 arc-second, vertically referenced to MHW was developed for the PMEL NOAA Center for Tsunami Research. The best available digital data from U.S. federal, state and local agencies, and academic institutions were obtained by NGDC, shifted to common horizontal and vertical datums, and evaluated and edited before DEM generation. The data were quality checked, processed and gridded using *ArcGIS*, *Fledermaus*, *FME*, *GDAL*, *GMT*, *Gnuplot*, *GEODAS*, *Quick Terrain Modeler*, *MB-System*, and *VDatum* software.

Recommendations to improve the DEM, based on NGDC's research and analysis, are listed below:

- Conduct bathymetric–topographic lidar surveys within Hanalei Bay, Hawaii.
- Conduct higher resolution bathymetric surveys for coral reef areas.

5. Acknowledgments

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6. References

Electronic Navigational Chart #19381, 3rd Edition, 2010. Island of Kauai. Scale 1:80,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Raster Nautical Chart #19380, 15th Edition, 2003. Oahu to Niihau. Scale 1:247,482. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

Raster Nautical Chart #19385, 8th Edition, 2003. North Coast of Kauai - Haena Point to Kepuhi Point. Scale 1:20,000. U.S. Department of Commerce, NOAA, National Ocean Service, Coast Survey.

7. Data Processing Software

ArcGIS v. 10 – developed and licensed by ESRI, Redlands, California, http://www.esri.com/

ESRI World Imagery (ESRI_Imagery_World_2D) – ESRI ArcGIS Resource Centers http://resources.esri.com/arcgisonlineservices/

FME 2010 GB – Feature Manipulation Engine, developed and licensed by Safe Software, Vancouver, BC, Canada, http://www.safe.com/.

Fledermaus v. 7.0.0 – developed and licensed by Interactive Visualization Systems (IVS 3D), Fredericton, New Brunswick, Canada, http://www.ivs3d.com/

GDAL v. 1.7.1 – Geographic Data Abstraction Library is a translator library maintained by Frank Warmerdam, http://www.gdal.org/

GEODAS v. 5 – Geophysical Data System, freeware developed and maintained by Dan Metzger, NOAA National Geophysical Data Center, http://www.ngdc.noaa.gov/mgg/geodas/.

GMT v. 4.3.4 – Generic Mapping Tools, freeware developed and maintained by Paul Wessel and Walter Smith, funded by the National Science Foundation, http://gmt.soest.hawaii.edu/.

Gnuplot v. 4.2 – shareware developed and maintained by Thomas Williams, Colin Kelley, Russell Lang, Dave Kotz, John Campbell, Gershon Elber, Alexander Woo http://www.gnuplot.info/

MB-System v. 5.1.0 – shareware developed and maintained by David W. Caress and Dale N. Chayes, funded by the National Science Foundation, http://www.ldeo.columbia.edu/res/pi/MB-System/

Persistence of Vision Pty. Ltd (POV Ray) v. 3.6 – Persistence of VisionTM Raytracer. Persistence of Vision Pty., Williamstown, Victoria, Australia, http://www.povray.org/

Quick Terrain Modeler v. 7.0.0 – Lidar processing software developed by John Hopkins University's Applied Physics Laboratory (APL) and maintained and licensed by Applied Imagery, http://www.appliedimagery.com/.